AFRL-PR-WP-TP-2007-211

SAFT Li-ion TECHNOLOGY FOR HIGH RATE APPLICATIONS (PREPRINT)

Kamen Nechev, Bridget Deveney, Teymur Guseynov, John Erbacher, and Stephen Vukson

NOVEMBER 2006

Approved for public release; distribution unlimited.

STINFO COPY

© 2006 SAE International

This work was funded in whole or in part by Department of the Air Force contract F33615-03-D-2350-0001. The U.S. Government has for itself and others acting on its behalf a paid-up, nonexclusive, irrevocable worldwide license to use, modify, reproduce, release, perform, display, or disclose the work by or on behalf of the U.S. Government.

PROPULSION DIRECTORATE
AIR FORCE MATERIEL COMMAND
AIR FORCE RESEARCH LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS**.

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
November 2006	Conference Paper Preprint	12/22/2005 – 09/12/2006

4. TITLE AND SUBTITLE
SAFT Li-ion TECHNOLOGY FOR HIGH RATE APPLICATIONS (PREPRINT)

5a. CONTRACT NUMBER F33615-03-D-2350-0001
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 62203F

6. AUTHOR(S)
Kamen Nechev, Bridget Deveney, and Teymur Guseynov (SAFT America, Inc.)
John Erbacher and Stephen Vukson (AFRL/PRPS)

5d. PROJECT NUMBER 3145
5e. TASK NUMBER 22
5f. WORK UNIT NUMBER A4

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SAFT America, Inc.
107 Beaver Court
Cockeysville, MD 21030

Electrochemistry and Thermal Sciences Branch (AFRL/PRPS)
Power Division
Propulsion Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7251

8. PERFORMING ORGANIZATION REPORT NUMBER
2006-01-3021

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Propulsion Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7251

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-PR-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-PR-WP-TP-2007-211

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
Conference paper submitted to the Proceedings of the 2006 SAE Power Systems Conference, published by SAE International. © 2006 SAE International. This work was funded in whole or in part by Department of the Air Force contract F33615-03-D-2350-0001. The U.S. Government has for itself and others acting on its behalf a paid-up, nonexclusive, irrevocable worldwide license to use, modify, reproduce, release, perform, display, or disclose the work by or on behalf of the U.S. Government.

PAO Case Number: AFRL/WS 06-2248; Date cleared: 21 Sep 2006. Paper contains color.

14. ABSTRACT
SAFT will present an update of its state-of-the art Very High Power (VHP) Lithium-ion (Li-ion) technology. The VHP cells are currently being qualified for use in military aircraft applications as well as in future military hybrid vehicles. Additionally, their use in Directed Energy Weapon (DEW) systems is also being explored.

15. SUBJECT TERMS
batteries, high rate, aircraft, directed energy, lithium-ion

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
Unclassified	Unclassified	Unclassified	SAR	10	John K. Erbacher
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

2006-01-3021

SAFT Li-ion Technology for High Rate Applications

Kamen Nechev, Bridget Deveney, Teymur Guseynov
SAFT America, 107 Beaver Court, Cockeysville, MD 21030

John Erbacher, Stephen Vukson
Air Force Research Laboratory, AFRL/PRPS, Wright-Patterson AFB, OH 45433

Copyright © 2006 SAE International

ABSTRACT

SAFT will present an update of its state-of-the art Very High Power (VHP) Lithium-ion (Li-ion) technology. The VHP cells are currently being qualified for use in military aircraft applications as well as in future military hybrid vehicles. Additionally, their use in Directed Energy Weapon (DEW) systems is also being explored.

INTRODUCTION

In the 1990s SONY introduced Li-ion electrochemistry and ever since that time this young technology has changed the world of batteries. It established itself as the premier high energy system of choice for all portable electronics devices. Li-ion cells are found today in every laptop computer and almost every mobile phone and handheld communication device sold across the world.

More recently Li-ion electrochemistry has taken on new challenges. The technology is being developed for employment as power source for hybrid electric vehicles (HEV), power tools, telecomm back up power, etc.. SAFT has been among the pioneers in expanding the capabilities of this new system. In 1995 through work sponsored by the Department of Energy under the Partnership for a New Generation of Vehicle (PNGV), the SAFT facility located in Cockeysville, Maryland started developing the power capability of the Li-ion system. SAFT utilized a number of technical innovations to successfully develop high power Li-ion technology capable of meeting the requirements of HEVs [1]. In early 2002 SAFT further established its leadership position in the area of high power Li-Ion through designing the technology for pulse power applications. This work was initiated under DARPA contract [2] and the effort continued subsequently under funding from the US Air Force. SAFT is currently working on further improvement of VHP technology for use in aircraft and DEW applications.

CURRENT STATUS OF SAFT VHP TECHNOLOGY

VHP technology found its first practical application as the system of choice for the 270V battery in an advanced fighter aircraft. Under qualification at SAFT is a battery consisting of VL4V cells in series. These cells represent the industrially mature version of the VHP state-of-the art production technology. This VL4V's excellent low temperature performance enables the operation of a battery meeting the demanding requirements of the aircraft application. The technology is capable of delivering high power pulses at very low temperature (-40 °C) over the lifetime of the cell even after excursions to high temperature (72 °C).

SAFT has three different cell sizes available with the VHP technology in them. VL4V is the smallest cell and although it was developed for aircraft use it is also the test vehicle for innovations for the technology. VL12V was developed specifically for a military hybrid vehicle and it is essentially twice as large as the VL4V cell. VL8V is an intermediate cell. Its targeted use is in several specific DEW prototype systems. The cells employ very much the same electrochemistry as they are simply a scale up of the power and energy. Figure 1 is a photo of the three VHP cells.

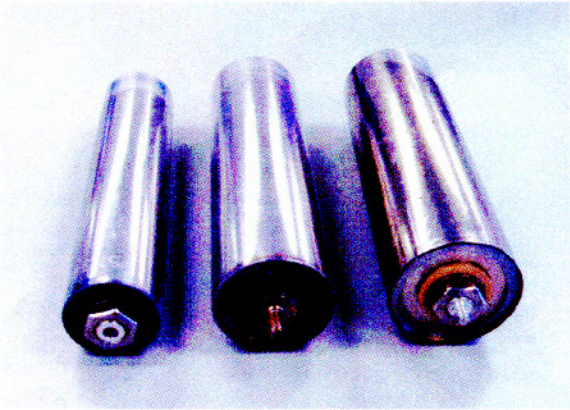

Figure 1: Photo of SAFT family of VHP cells.

Figure 2 shows the discharge voltage curves of the standard VL4V cell under different constant current discharges at 25, 0 and -20 °C.

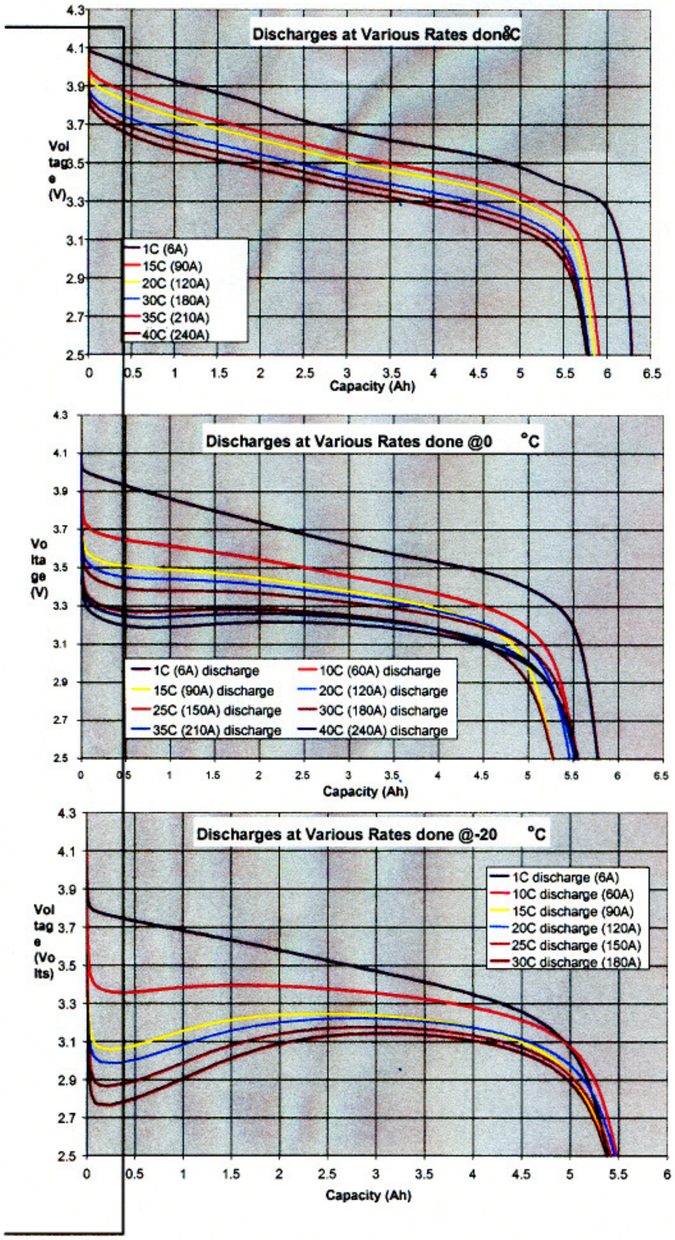

Figure 2: Constant current discharge of VL4V at different temperatures

TABLE 1 summarizes the physical and performance properties of the VHP cells currently offered by SAFT. In general the technology is capable of 8kW/kg in 2-second pulses as well as 12kW/kg on millisecond long pulses. This power performance is superior to performance of super-capacitors and is provided at fairly high energy content. The specific energy of the VHP cells is around 65 Wh/kg. Around 70% of this energy is available at the very high power level; the rest is also usable but at lower rates (<10C).

TABLE 1: SAFT Very High Power cells

	VL4V	VL8V	VL12V
Capacity, Ah	6	8.5	12.5
Energy, Wh	22	31	45.5
Power (100% SOC), W			
200 milliseconds	3800	5650	N/A
2 seconds	2500	3800	5500*
15 seconds	2000	3000	4000*
Weight, grams	320	470	600
Diameter, mm	34	41	47
Length, mm	156	156	156

* VL12V cell is not completely evaluated yet

Developing good low temperature performance is done by designing the electrode morphology and tailoring the electrolyte for the specific need. As a rule an electrolyte good for low temperature suffers serious deficiencies at elevated temperatures. SAFT has a patented electrolyte system, which in addition to the excellent low temperature performance, shown in Figure 2, is capable of operating at high temperature as well. Exposure to high temperature has a detrimental effect on cell calendar and cycle life and typically use at temperatures greater than 60 °C is not recommended. However, in certain applications like military HEV the battery could experience extreme temperatures due to operating conditions. Figure 3 shows cycling of a standard VL4V cell at 80 °C. The cell is identical to the one used in the tests shown in Figure 2. Cycling was done at 1C charge and discharge rate with a cut off of 2.5V.

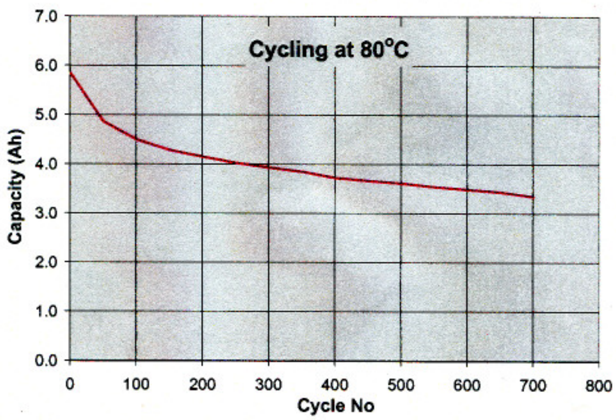

Figure 3: Cycling of VL4V at 80 °C

Under the USAF program SAFT focused its development efforts in two main areas. These are improvement of mechanical bussing and further optimization of the electrochemistry. The goals encompass maximizing of specific power, increase of cycle life under heavy load conditions as well as minimizing the heat generation. These goals are not mutually exclusive and often improving on one benefits the other.

It has been experimentally determined that the main source of heat generation in SAFT cylindrical cells is not electrochemical. The bussing of both the positive and negative terminals is predominantly responsible for I^2R heating. Therefore it was logical to expect that optimizing the cell interconnectivity would benefit both power and the need for thermal management. Testing was performed to identify impedance bottle necks and direct development efforts. A standard VL4V cell (used in the fighter 270V battery) was subjected to a 10 second 500A constant current discharge. Temperature was monitored for 15 minutes after the test on seven locations along the cell. It is important to note that the cell is can negative (the can is electrically and thermally connected to the negative electrode). Figure 4 shows the temperature rise on the standard VL4V cells. The position of the 7 thermocouples on the cells is indicated on the charts.

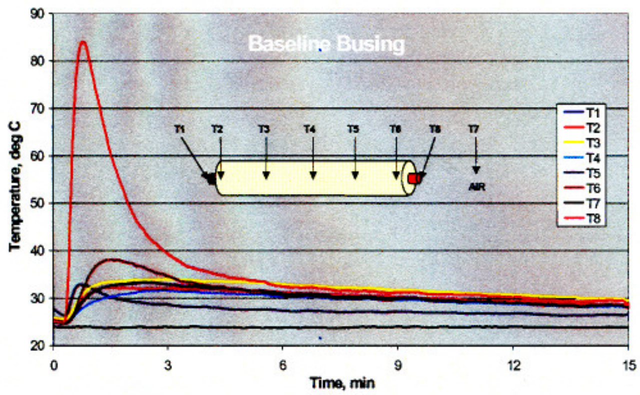

Figure 4: Temperature measured on standard VL4V cell during and after 10 seconds discharge at 500A.

The results strongly indicate that most of the heat is generated in the positive terminal bussing of the cell. The second highest temperature is measured right next to the positive terminal with some lag in time. As a result SAFT focused its effort on the positive end of the cell. Design changes were first tried on VL4V cell containing standard electrochemistry. A new mechanical feed through was implemented, which improved the impedance of the bussing and the cell. The AC impedance of the VL4V cell, measured through the 1000Hz method, was reduced by about 35%. Figure 5 shows a photo of the redesigned VL4V cell.

Figure 5: New mechanical feed through for VL4V cell

A group of cells was built and tested. A cell from the group was subjected to the same 500A constant current pulse and temperature was measured the same way. Figure 6 shows the outcome of the test confirming that the change had a beneficial effect on heat generation.

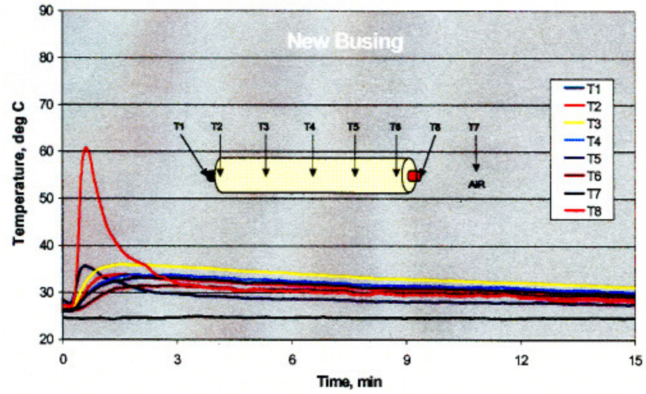

Figure 6: Temperature measured on improved VL4V cell having the new bussing.

Although the new bussing reduced the maximum discharge temperature significantly it is apparent that there is more room for improvement. The positive terminal still remains the hottest point. Design optimization of the VL4V cell to further reduce I^2R heating and increase manufacturability is ongoing. SAFT is also working on redesign of the negative terminal to optimize high rate charging.

As a result of this successful first effort, the new VL12V cell was designed with the improved high power bussing. The cell benefits from the improved bussing from the very beginning enabling very high currents rate. Since the cell contains the same electrochemistry its power capabilities are excellent over a wide temperature range. Figure 7 shows the behavior of the cell during 18 seconds long 200A constant current pulses at different temperatures. The test is done at 100% state of charge.

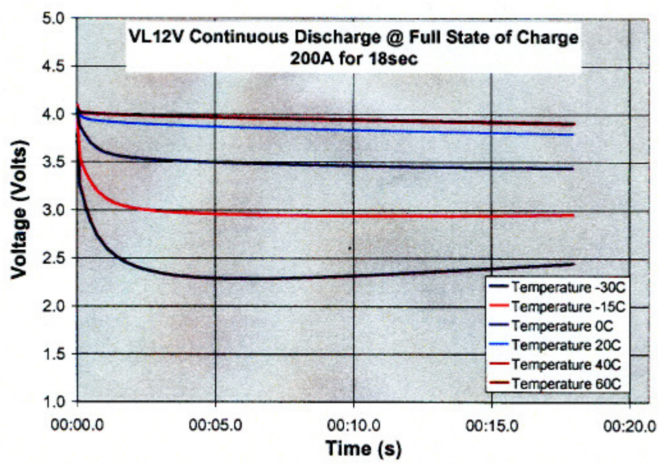

Figure 7: Pulse power of the VL12V cell at different temperature at 100% SOC.

The same test was performed at 50% SOC. Figure 8 shows the performance of a VL12V cell under these test conditions.

This improvement enables cycling to be performed at high rate with minimum cooling required. The Li-ion couple can tolerate high temperature up to 65 °C without any detrimental effects to life and performance. As shown in Figure 3 operating temperatures between 65 and 90 °C are only harmful for the remaining life of the chemistry but do not represent a safety hazard. Operation at 90 °C and above carries the risk of pushing the system into thermal runway.

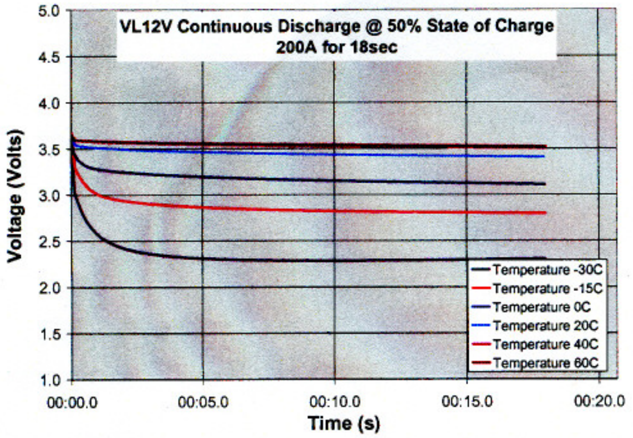

Figure 8: Pulse power of the VL12V cell at different temperature at 50% SOC.

SAFT has been testing its VHP technology under several use profiles [3]. In the case of a simulated Airborne Active Denial System (AADS) the battery operates in hybrid mode in parallel with a High Temperature Super-Conducting (HTSC) generator. Testing at SAFT was performed on a VL4V cell containing the improved bussing using 350A during discharge (15 seconds) and 155A for the recharge (34 seconds). The cell cycles about 25% of its capacity in and out. All cycling is performed around 3.7V cell voltage.

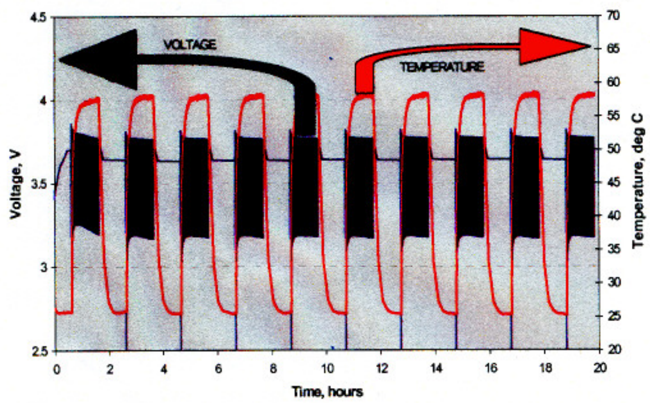

Figure 9: Cycling of VL4V cell at 350A/150A rate - eight 75-cycle sequences between diagnostics.

The charge/discharge cycle is repeated 75 times for one hour followed by one hour of rest. After completing eight sequences for a total of 600 cycles the cell is brought back to 3.7V. During cycling temperature increases until it reaches a steady state. With the increase of cell temperature, electrochemical polarization and voltage hysteresis between charge and discharge are reduced.

The VL4V cell cycled for 22,000 cycles, Figure 10, and then it was stopped. Since only 25% of the energy is used in each cycle the actual end of life would be determined by the inability of the power system to meet voltage regulations. The loaded voltage of the battery during charge and discharge is dependent on the charge and discharge impedance. With use the battery impedance increases and the actual conformance to the specified voltage window can be calculated.

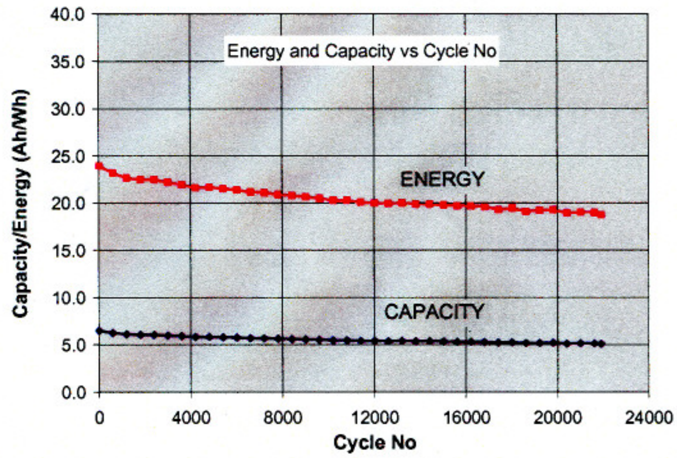

Figure 10: Energy and capacity change.

CONCLUSION

SAFT VHP technology provides a long lasting lightweight high power source for a variety of military applications like aircraft, military HEV, etc. With its extreme power capabilities the technology will be also capable of supporting emerging DEW technologies.

REFERENCES

1. K. Nechev, M. Saft, G. Chagnon, A. Romero, T. Sack, T. Matty, "High Power Li-Ion Technology for 42V Batteries", 3rd Advanced Automotive Battery Conference, Nice, France 2003
2. K. Nechev, J. Erbacher, S. Vukson, B. Deveney, "Progress in SAFT Very High Power Lithium Ion Technology", 43st Power Sources Conference, Philadelphia PA, June2006
3. K. Nechev, J. Erbacher, S. Vukson, B. Deveney, T. Matty, "Lithium Ion Pulse Power for Directed Energy Power Source", 8th DEPS, Hawaii, November 2005.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

DEW: Directed Energy Weapon
HEV: Hybrid Electric Vehicle
I^2R: Current squared multiplied by resistance
Li-ion: Lithium-ion
SOC: State of Charge
VHP: Very High Power